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INCORPORATION OF ADVECTION OF HEAT BY MEAN WINDS AND BY OCEAN CURRENTS IN A THERMODYNAMIC MODEL FOR LONG-RANGE WEATHER PREDICTION

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ABSTRACT

By means of adequate parameterizations, the advection of heat by the mean wind and that by ocean currents are incorporated in a thermodynamic model for long-range weather prediction.

Numerical experiments with the revised model for a single case (January 1968) show that nonnegligible anomalies of wind and ocean currents are generated. These introduce important changes in the predicted surface temperature and in the 700-mb temperature anomalies. Furthermore, the predicted monthly anomalies of temperature are in good agreement with the observations and are better than those obtained when advection by mean wind is neglected.

An evaluation of the predictions by the model of the anomalies of the mean monthly surface air temperature for the whole year 1969 over the conterminous United States is presented; and it is shown that, for this period, the skill improves considerably when advection by the mean wind is included.

Normal temperatures are computed using normal observed geostrophic mean winds in the midtroposphere and climatological seasonal values of ocean currents.

For January, the effect of introducing advection by the prescribed observed normal geostrophic wind is to move toward the east the midcontinental troughs and midoceanic ridges that were obtained without advection. The resultant temperature distribution for the Northern Hemisphere at 700 mb is in remarkably good agreement with the observed values.

1. INTRODUCTION[1]

Considerable success has been achieved in recent years in short and medium range numerical prediction (Shuman and Hovermale 1968). As time goes on, the prediction of the detailed evolution of weather becomes less and less accurate; the energy sources and sinks become of greater importance; and for a period of about 1 or 2 weeks, one of the more difficult weather prediction problems is encountered, with the complex coupling of both thermodynamical and dynamical effects. For longer periods of time, the prediction of the detailed evolution of weather can probably no longer be attempted successfully. However, one can try instead to predict the mean state over the considered period of time.

Furthermore, as the scale of time is increased, a period of the order of a month or a season is reached at which the solution probably has only a weak dependence on the dynamical equations and is mainly governed by the thermodynamical ones. We will, therefore, postulate that in this case a first approximation to the problem can be achieved by using the conservation of thermal energy as a prognostic equation and subordinate to this the other conservation laws that are used diagnostically. However, due to the scale of time, the entire atmosphere-ocean-continent system must be dealt with, instead of the atmosphere alone, and an attempt must be made to predict the behavior of the whole system.

The basic predicted variable is the average temperature, and quantities are dealt with for the extended period of time being considered. In this way, an attempt is made to predict the mean temperature of the troposphere and of the surface of the oceans and continents.

By fixing the scale of time, the equations are simplified and, furthermore, it is possible to introduce the average heating corresponding to the given period. Therefore, the solution can be obtained in one or few time steps. In this way, an attempt is made to explain climatology and to make numerical weather predictions for a month or a season, even though the detailed evolution of the weather for much shorter periods cannot be predicted.

The basic prognostic equations used are the conservation of thermal energy in the troposphere and in the surface of the earth. The equations contain the storage of energy and the horizontal transport of heat in the oceans and in the troposphere, the excess of radiation in the troposphere and at the surface of the earth, the sensible heat given off from the surface to the troposphere, the heat lost by evaporation at the surface, and the heat gained by the troposphere by condensation of water vapor in the clouds. The albedo of the surface of the earth and the cloudiness are included as parameters in the model.

In a series of papers (Adem 1962, 1963, 1964*a*, 1964*b*, 1965*c*), a time-averaged model of the atmosphere-ocean-continent system based on this approach has been developed. The model was initially applied to compute the zonally averaged climatological (or normal) temperature distributions (Adem 1962, 1963). Afterward, it was applied to the Northern Hemisphere with a realistic distribution of continents and oceans to compute the climatological monthly and seasonal distribution of midtropospheric temperatures and surface (oceans and con-

[1] This is an updated version of the introduction given by the author at the Symposium on the Research and Development Aspects of Long-Range Forecasting at Boulder, Colo., in 1964 (Adem 1965*a*).

tinents) temperatures (Adem 1964*a*, 1964*b*); and a method was developed to apply the model to the prediction, for periods of a month, of the departures from normal of surface and midtropospheric temperature and precipitation (Adem 1964*b*, and 1965*c*).

Since December 1965, monthly predictions of surface temperature and precipitation have been carried out using the model, and a preliminary evaluation of the skill of the predictions has been published (Adem and Jacob 1968 and Adem 1969*a*).

There are many possibilities for the improvement of the current model that we hope will yield improvement in the skill of the predictions. An improved model is now available that includes advection of heat by ocean currents (Adem 1970) as well as improvements in the advection of heat by the mean wind. Furthermore, it includes a variety of options to test different parameterizations of the heating components.

This paper deals mainly with the parameterization and incorporation in the model of advection of heat by the mean wind, but the numerical experiments were also designed to study the effect of advection by ocean currents.

2. DESCRIPTION OF THE MODEL

The model used in these experiments is described in detail in several papers by the author (Adem 1964*b*, 1965*b*, 1965*c*, 1970). Therefore, only a brief description of it will be given here.

The conservation of thermal energy (first law of thermodynamics) is applied to the upper layer of the oceans (down to about 100 to 50 m), the upper layer of the continents (negligible depth), and the vertically integrated one-layer atmosphere (up to about 10 km).

The equation for the ocean layer (Adem 1970) is

$$H_s\left(\frac{\partial T_s'}{\partial t}+\mathbf{v}_{s_T}\cdot\nabla T_s'-K_s\nabla^2 T_s'\right)=E_s-G_2-G_3 \qquad (1)$$

where ∇ is the two-dimensional horizontal gradient operator; T_s' is the departure of the surface ocean temperature from a constant value T_{s_0}, $T_{s_0}\gg T_s'$; $H_s=h\rho_s c_s$, ρ_s is a constant density and c_s is the specific heat; h is the depth of the layer; $\mathbf{v}_{s_T}$ is the horizontal velocity of the ocean currents; K_s is a constant austausch coefficient; E_s is the energy added by radiation; G_2 is the sensible heat given off to the atmosphere by vertical turbulent transport; and G_3 the heat lost by evaporation. The term $H_s\ \partial T_s/\partial t$ is the local rate of change of thermal energy; $H_s\mathbf{v}_{s_T}\cdot\nabla T_s'$ and $-H_sK_s\ \nabla^2 T_s'$ are the horizontal transport of thermal energy by mean ocean currents and by turbulent eddies, respectively.

In the continents, equation (1) reduces to

$$0=E_s-G_2-G_3. \qquad (1')$$

The conservation of thermal energy for the atmosphere is given by the following equation (Adem 1965*b*):

$$c_v a_0\frac{\partial T_m'}{\partial t}+\mathrm{AD}-c_v a_0 K\nabla^2 T_m'-c_v K\mathbf{b}\cdot\nabla T_m'=E_T+G_5+G_2 \qquad (2)$$

where T_m' is the departure of the mean atmospheric temperature from a constant value T_{m_0}, $T_{m_0}\gg T_m'$; c_v is the specific heat of air at constant volume; $a_0=\int_0^H \rho_0^*\,dz$; $\mathrm{AD}=c_v\mathbf{M}_a\cdot\nabla T_m'$, $\mathbf{M}_a=\int_0^H \rho_0^*\mathbf{v}_H^* dz$; and $\mathbf{b}=\int_0^H \nabla\rho^* dz$, where H is the constant height of the model atmosphere and ρ^* is the density given by

$$\rho^*=\rho\left(1+\frac{\beta(H-z)}{T_m-\beta H/2}\right)^{g/R\beta-1}. \qquad (3)$$

$T_m=T_{m_0}+T_m'$, ρ is a fixed constant density at $z=H$, β is the constant lapse rate used in the atmospheric layer, g is the acceleration of gravity, $\mathbf{v}_H^*$ is the horizontal component of the wind, ρ_0^* is the value of ρ^* obtained by replacing T_m by T_{m_0}, and K is the horizontal austausch coefficient for the atmosphere.

On the right side of equation (2), E_T is the heat energy added by radiation, G_5 is the energy added by condensation of water vapor in the clouds, and G_2 is the heat added by vertical turbulent transport from the surface.

On the left side, $c_v a_0\ \partial T_m'/\partial t$ is the local rate of change of thermal energy, and AD and $-c_v a_0 K\nabla^2 T_m'$ are the advection of thermal energy by the mean wind and by horizontal eddies, respectively.

The different heating components that appear in equations (1) and (2) will be expressed as functions of T_s', T_m', $\partial T_m'/\partial x$, and $\partial T_m'/\partial y$. For E_T, E_s, G_2, G_3, and G_5, we shall use the same parameterizations as in the previous experiments (Adem 1965*c* and Clapp et al. 1965).

In the model used up to now, we have made the following assumptions:

1. In equation (1), the horizontal transports of thermal energy by the mean ocean currents and by turbulent eddies are neglected.

2. In equation (2), the advection by mean wind is taken as zero or as advection by a prescribed normal mean wind.

3. The term $c_v K\mathbf{b}\cdot\nabla T_m'$ is neglected.

4. In equation (1), $\partial T_s'/\partial t$ is replaced by $(T_s'-T_{s_p}')/\Delta t$ where T_{s_p} is the value of T_s' in the previous month and Δt is the time interval taken as a month. Similarly, $\partial T_m'/\partial t$ in equation (2) is replaced by $(T_m'-T_{m_p}')/\Delta t$ where T_{m_p}' is the value of T_m' in the previous month.

Substituting the parameterized heating functions in equations (1) and (2) and using assumptions (1), (2), (3), and (4), we obtain two linear equations to compute T_m' and T_s'. Due to assumption (1), equation (1) becomes algebraic. Therefore, the problem is reduced to solving an elliptic differential equation of the type

$$K\nabla^2 T'_m + F''_1 \frac{\partial T'_m}{\partial x} + F'''_1 \frac{\partial T'_m}{\partial y} + F'_1 T'_m = F'_2 \tag{4}$$

where F'_1, F''_1, F'''_1, and F'_2 are known functions of the map coordinates x and y (Adem 1965c).

Assumptions (1), (2), (3), and (4) have reduced the integration problem to the solution of a linear second-order elliptic differential equation. However, we can remove (1) and (2) and still get the same type of integration problem.

In a recent paper (Adem 1970), an attempt to remove assumption (1) has been described in detail. Only a brief summary will be given here.

Considering that the term $H_s \partial T'_s/\partial t$ is of the same magnitude or larger than any one of the others in equation (1), one can attempt to solve equation (1) with forward or centered differences to obtain the predicted ocean temperature. The latter is then substituted in equation (2) in which we still use backward differences. This is done because in contrast with what happens in the oceans the storage term in the atmosphere is small compared with the heating functions. The integration problem is therefore reduced again to the solving of an elliptic differential equation for the tropospheric temperature.

For the total ocean current $\mathbf{v}_{s_T}$, we assume

$$\mathbf{v}_{s_T} = \mathbf{v}_{s_W} + (\mathbf{v}_s - \mathbf{v}_{s_N})$$

where $\mathbf{v}_{s_W}$ is the observed normal seasonal ocean current, $\mathbf{v}_s$ is the pure wind drift current, and $\mathbf{v}_{s_N}$ is the corresponding normal wind drift current.

The components of the vector $\mathbf{v}_s$ are computed from the following formulas:

$$u_s = C_1 \frac{0.0126}{\sqrt{\sin\phi}} (u_a \cos\theta + v_a \sin\theta) \tag{5}$$

and

$$v_s = C_1 \frac{0.0126}{\sqrt{\sin\phi}} (v_a \cos\theta - u_a \sin\theta) \tag{6}$$

where the directions of the coordinate axes are arbitrarily chosen, u_s and v_s are respectively the x and y components of the current, u_a and v_a are respectively the x and y components of the surface wind, ϕ is the latitude, C_1 is a constant parameter, and θ is the angle that measures the direction of the vector surface ocean current to the right of the surface wind direction.

The detailed derivation of equations (5) and (6) has been given elsewhere (Adem 1970) and is based on Ekman's formulas.

The components of $\mathbf{v}_{s_N}$ are obtained using normal values of the surface wind components in equations (5) and (6).

In the experiments reported in this paper, we have used the values $C_1=1$ and $\theta=45°$ in equations (5) and (6). These are the same values used by Namias (1959) who apparently was the first to apply Ekman's results to compute changes in mean monthly anomalies of ocean temperature due to advection by ocean currents.

3. PARAMETERIZATION AND INCORPORATION IN THE MODEL OF THE ADVECTION OF THERMAL ENERGY BY THE MEAN WIND

The advection of thermal energy (denoted by AD) in an atmospheric layer of height H is defined by

$$\mathrm{AD} = c_v \int_0^H \rho^* \mathbf{v}^*_H \cdot \nabla T^* dz \tag{7}$$

where c_v is the specific heat of air at constant volume and $\mathbf{v}^*_H$, ρ^*, and T^* are the three-dimensional fields of the horizontal wind, density, and temperature, respectively.

We shall express the temperature by

$$T^* = -\beta(z-H) + T \tag{8}$$

where β is the mean lapse rate in the atmospheric layer and T is the temperature at $z=H$.

Using equation (8) together with the equations of hydrostatic equilibrium and perfect gas, we obtain

$$p^* = p(T^*/T)^\alpha \tag{9}$$

and

$$\rho^* = \rho(T^*/T)^{\alpha-1} \tag{10}$$

where $\alpha = g/R\beta$, p and ρ are respectively the values of the pressure and density at $z=H$, g is the acceleration of gravity, and R is the gas constant. Since $T_m = \beta H/2 + T$, equation (10) is equivalent to (3). Furthermore, when β is horizontally constant and ρ^* is replaced by ρ^*_0, formula (7) gives the advection term used in equation (2).

Using the geostrophic wind equations together with equation (8), (9), and (10), we can write equation (7) as

$$\mathrm{AD} = F_8 J(T,p) + F_9 J(T,\beta) + F_{10} J(p,\beta) \tag{11}$$

where

$$F_8 = \frac{c_v T}{f\beta(\alpha+1)} \left[1 - \left(\frac{T_a}{T}\right)^{\alpha+1}\right]. \tag{12}$$

$T_a = T + \beta H$, and F_9 and F_{10} are also functions of β, T, and p.

Using equation (11), we shall compute the advection of thermal energy by the mean wind in an 11-km layer. As input data, we shall use the 500-mb temperature and height and the observed normal mean lapse rate in the layer. Note that β is assumed constant with elevation and time but varies horizontally over the earth.

Using equations (8) and (9), we can compute from these data T and p; and from equation (11), the advection AD. The results of the computations for February 1962 are shown in figure 1A; figure 1B is the computed advection for the same month using a constant lapse rate equal to 6.5 (°C) km^{-1}.

Comparison of 1B with 1A shows that the advection of thermal energy by the mean geostrophic wind is very well

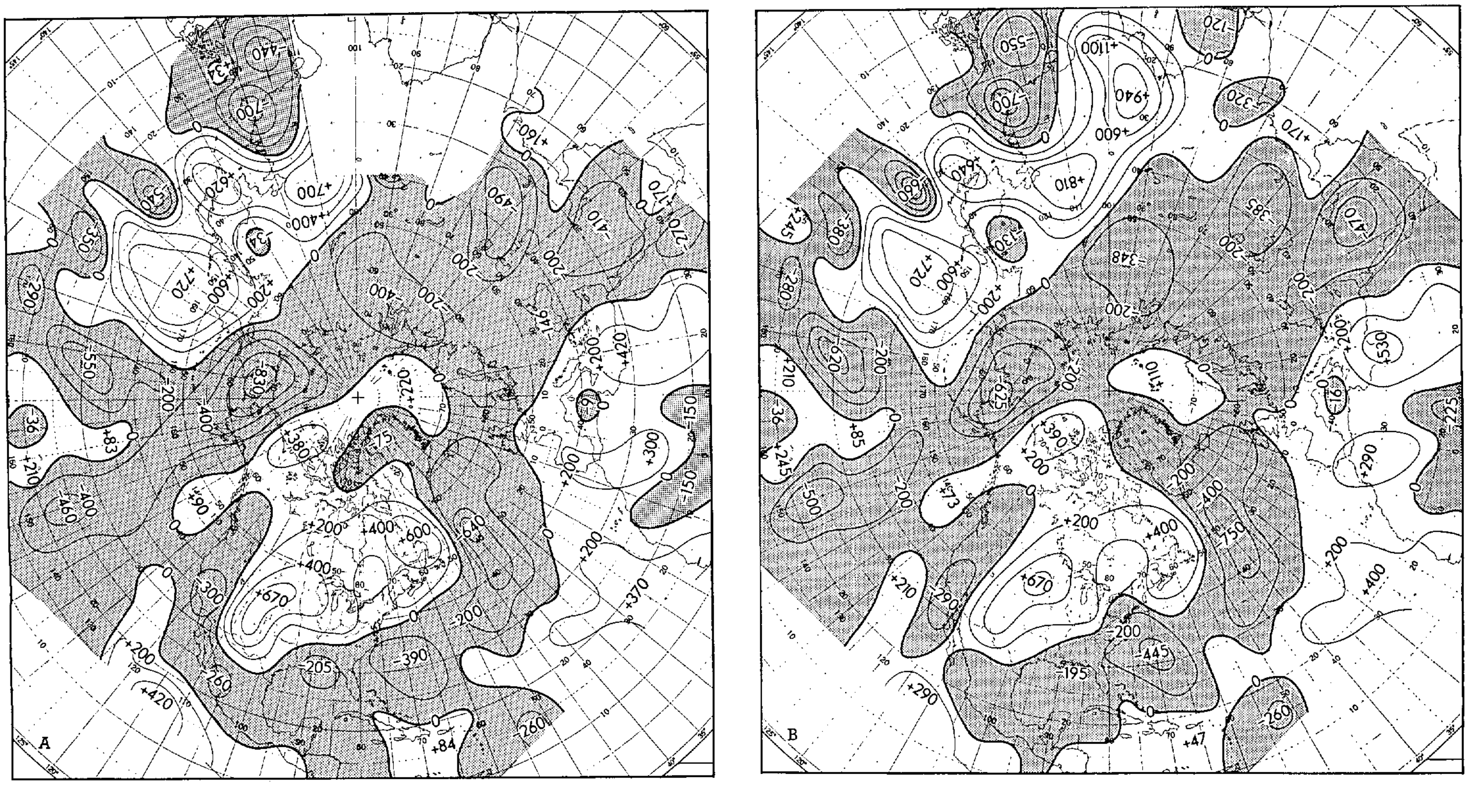

FIGURE 1.—Advection of thermal energy by the mean wind, in cal cm^{-2} day^{-1}, for February 1962, computed from equation (11): (A) using the observed normal mean lapse rate and (B) using a lapse rate equal to 6.5 (°C) km^{-1}.

approximated by the first term of equation (11):

$$\mathrm{AD}=F_8 J(T, p). \tag{13}$$

The other two terms drop out when using a constant lapse rate.

In the present formulation of the thermodynamic model, we require linear functions of the different terms; therefore despite its simplicity, equation (13) cannot be used unless we add some extra information that allows us to compute p. In the present model in which we use assumption (2), we have two options.

Option 1. The density ρ at the top of the atmospheric layer is assumed constant. This condition, together with the use of a constant lapse rate, implies that the isotherms coincide with the isobars. Therefore, AD=0.

Option 2. This option in the present model is to prescribe the normal values of p, a procedure equivalent to assuming advection by the normal mean wind in the model.

In a more advanced version of the model now being developed, another alternative will be tested that consists in adding a new equation to compute the pressure tendency. This equation can be derived by assuming that the vertical wind is zero at the top of the layer. The derivation for a layer of finite height has been outlined by Kasahara and Washington (1967).

The way in which this pressure tendency is coupled with the equations of conservation of thermal energy in the troposphere and surface of the earth is discussed elsewhere (Adem 1969*b*). The results of the numerical experiments will determine the extent to which this approach is successful and will be reported later.

The main purpose of this paper is to propose and test new alternatives for the parameterization of advection by the mean wind that have the advantage of keeping the model within its present level of simplicity and can be tested with only minor changes in the computer program.

In addition to the two options already considered and tested, we shall include the options described below.

Option 3. We shall assume

$$\mathbf{v}_H^*=\mathbf{v}_{N_{ob}}^*+(\mathbf{v}^*-\mathbf{v}_N^*) \tag{14}$$

where $\mathbf{v}_H^*$ is the total horizontal wind used in the model, $\mathbf{v}_{N_{ob}}^*$ is the normal observed geostrophic wind, $\mathbf{v}^*$ is the prediction horizontal wind, and $\mathbf{v}_N^*$ is the predicted normal horizontal wind.

Assuming a horizontally constant lapse rate and substituting equations (8) and (14) in equation (7), we obtain

$$\mathrm{AD}=c_v \nabla T \cdot \int_0^H \rho^*(\mathbf{v}_{N_{ob}}^*+\mathbf{v}^*-\mathbf{v}_N^*)dz. \tag{15}$$

The $\mathbf{v}_{N_{ob}}^*$ is obtained substituting equations (9) and (10) in the geostrophic wind formulas. The resulting formulas for the case of a horizontally constant lapse rate are

$$u^*_{N_{ob}}=-\frac{RT^*_{N_{ob}}}{fp_{N_{ob}}}\frac{\partial p_{N_{ob}}}{\partial y}+\frac{(H-z)}{fT_{N_{ob}}}g\frac{\partial T_{N_{ob}}}{\partial y} \tag{16}$$

and

$$v^*_{N_{ob}}=\frac{RT^*_{N_{ob}}}{fp_{N_{ob}}}\frac{\partial p_{N_{ob}}}{\partial x}-\frac{(H-z)}{fT_{N_{ob}}}g\frac{\partial T_{N_{ob}}}{\partial x} \tag{17}$$

where $u^*_{N_{ob}}$, $v^*_{N_{ob}}$ are the x and y components of $\mathbf{v}^*_{N_{ob}}$ and where $T^*_{N_{ob}}=T_{N_{ob}}+\beta(H-z)$.

Since we are going to use 700-mb data, $p_{N_{ob}}$ and $T_{N_{ob}}$ are computed from the following formulas

$$p_{N_{ob}}=(700\text{ mb})\left(\frac{T_{7_{N_{ob}}}+\beta(H_{7_{N_{ob}}}-H)}{T_{7_{N_{ob}}}}\right)^{\alpha}$$

and

$$T_{N_{ob}}=\beta(H-H_{7_{N_{ob}}})+T_{7_{N_{ob}}}$$

where $T_{7_{N_{ob}}}$ and $H_{7_{N_{ob}}}$ are the given observed normal 700-mb temperature and height, respectively. The $\mathbf{v}^*$ is obtained from equations (16) and (17) upon replacing $u^*_{N_{ob}}$, $v^*_{N_{ob}}$, $p_{N_{ob}}$, and $T_{N_{ob}}$ by u^*, v^*, p, and T, respectively. Furthermore, we will use the perfect gas equation and the assumption that the density at the top of the atmospheric layer is a constant (Adem 1967). The resulting formulas are

$$u^*=-\frac{R}{fT}\left(T^*-(H-z)\frac{g}{R}\right)\frac{\partial T}{\partial y} \tag{18}$$

and

$$v^*=\frac{R}{fT}\left(T^*-(H-z)\frac{g}{R}\right)\frac{\partial T}{\partial x}. \tag{19}$$

Similar formulas are obtained for $\mathbf{v}^*_N$. Substituting equations (10), (16), (17), (18), (19), and the formulas for $\mathbf{v}^*_N$ in equation (15), we obtain

$$\text{AD}=F_8J(T,p_{N_{ob}})+F''_8J(T,T_{N_{ob}})-F'_8J(T,T_N) \tag{20}$$

where F_8 is given by equation (12) and

$$F'_8=\frac{p}{T}\left(1-\frac{g}{R\beta}\right)F_8-\frac{g}{f\beta}F_2,$$

$$F_2=c_v\int_0^H\rho^*dz=\frac{c_vp}{g}\left[\left(\frac{T_a}{T}\right)^{\alpha}-1\right],$$

and

$$F''_8=F'_8-\frac{p}{T}F_8.$$

In the normal case, the last term on the right-hand side of equation (20) is equal to zero.

For use in the model, we replace equation (20) by

$$\text{AD}=(F_8)_0J(T'_m,p_{N_{ob}})+(F''_8)_0J(T'_m,T_{N_{ob}})-(F'_8)_0J(T'_m,T'_{m_N}) \tag{21}$$

where $(F_8)_0$, $(F'_8)_0$, and $(F''_8)_0$ are obtained from the above formulas using the constants T_0 and p_0 instead of T and p; where $T=T_0+T'$ and $p=p_0+p'$; and where $T'\ll T_0$ and $p'\ll p_0$. Furthermore, since $T_m=T_0+T'+\beta H/2$ and $T_{m_0}=T_0+\beta H/2$, $T'=T'_m$.

Since equation (21) is a linear function of $\partial T'_m/\partial x$ and $\partial T'_m/\partial y$, its use in equation (2), together with the linear parameterizations of the heating functions, yields an equation of the same type as equation (4).

In equation (21), the sum of the first two terms on the right-hand side gives the advection by the prescribed observed normal wind used in option 2. The last term is the only new addition and represents the advection of thermal energy by the anomalies of the wind predicted by the model.

If instead of equation (14) we assume that $\mathbf{v}^*_H=\mathbf{v}^*$, we obtain AD=0, which is option 1 already mentioned and used in numerous experiments by the author.

Options 4, 5, and 6 below are others in addition to equation (15) for the linearization of equation (14) that are included in the computer program.

Option 4.

$$\text{AD}=c_v\nabla T\cdot\int_0^H\rho^*\mathbf{v}^*_{N_{ob}}dz+c_v\nabla T_{N_{ob}}\cdot\int_0^H\rho^*(\mathbf{v}^*-\mathbf{v}^*_N)dz. \tag{22}$$

Option 5.

$$\text{AD}=c_v\nabla T_{N_{ob}}\cdot\int_0^H\rho^*(\mathbf{v}^*_{N_{ob}}+\mathbf{v}^*-\mathbf{v}^*_N)dz. \tag{23}$$

Option 6.

$$\text{AD}=c_v\nabla T_{N_{ob}}\cdot\int_0^H\rho^*\mathbf{v}^*dz. \tag{24}$$

4. NUMERICAL COMPUTATIONS

The type of data and values of coefficients used in the computations are described in previous papers (Adem 1964*b*, 1965*c*, 1970) and will not be repeated here.

Figure 2 shows the 700-mb normal temperature distributions for January. Figure 2A shows the computed values when the advection by mean wind is neglected; and figure 2B the values when it is included, using the normal observed geostrophic wind, $\mathbf{v}^*_{N_{ob}}$ (options 2, 3, or 4). Figure 2C is the observed normal 700-mb temperature distribution.

Figure 2A shows that, when advection by mean wind is neglected, the temperature field generated by the model has troughs in the middle of the Asiatic and American Continents and ridges in the middle of the Atlantic and Pacific Oceans.

Comparison of 2B with 2A shows that the main effect of introducing advection by the mean wind is to move the troughs and ridges eastward, yielding a temperature distribution in much better agreement with that observed (fig. 2C).

These results show that not only the effect of the distribution of oceans and continents with their associated

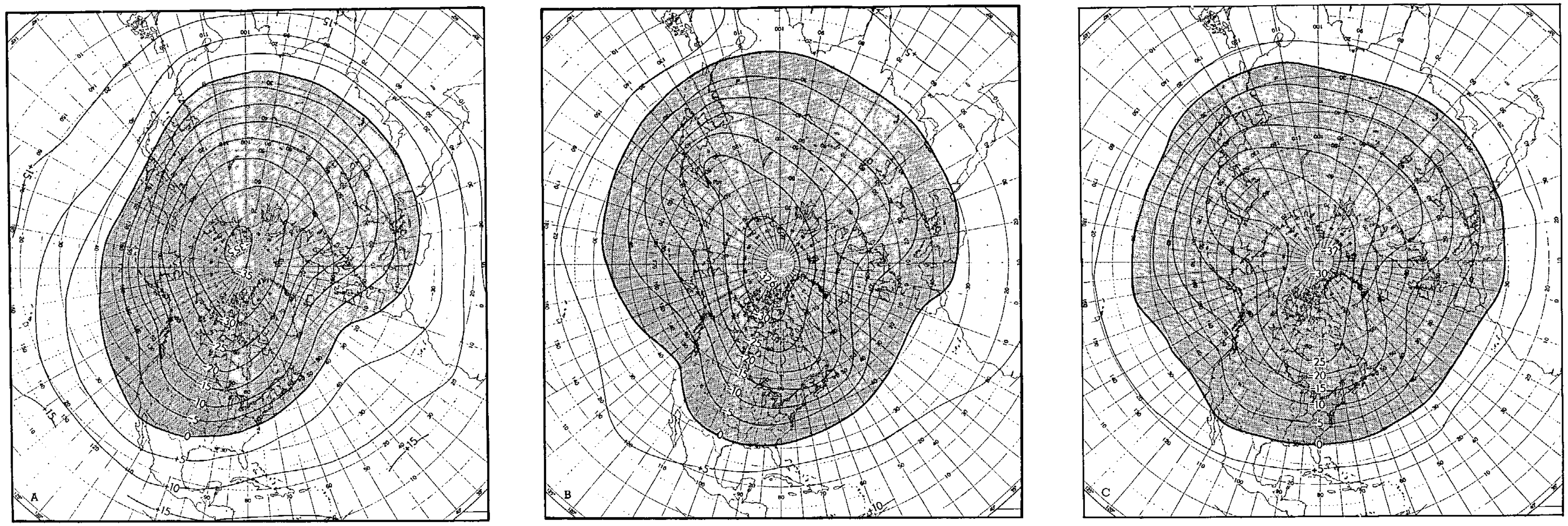

FIGURE 2.—Normal temperature for January at 700 mb in degrees Celsius: (A) computed when advection of heat by the mean wind is neglected; (B) computed when observed normal geostrophic winds are used in the mean-wind advection term; and (C) observed values.

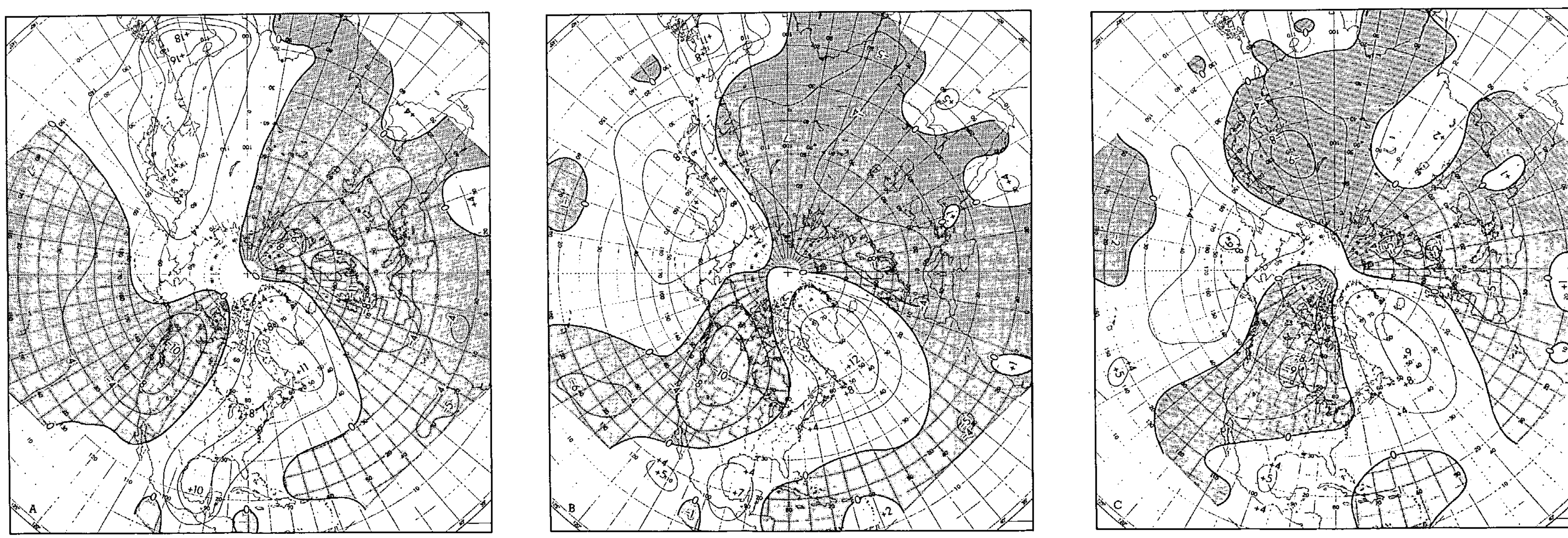

FIGURE 3.—Normal meridional wind component at 700 mb, in meters per second: (A) and (B) are computed, using equations (18) and (19), from the predicted temperature fields shown in figures 2A and 2B, respectively; and (C), observed geostrophic values.

heat sources and sinks but also the advection of heat is very important in determining the winter pattern of temperature and its associated circulation.

In this computation, we have used a value of the austausch coefficient K equal to 3×10^{10} cm^2 sec^{-1}. When K is taken equal to 2×10^{10} cm^2 sec^{-1}, we obtain patterns similar to those of figures 2A and 2B but with temperatures about 5°C lower at the Pole.

The temperature distribution of figure 2B was obtained upon prescribing the values of the observed normal geostrophic wind at 700 mb in the advection term (AD) of equation (2). It is interesting to compare these wind values with those obtained from the temperature fields predicted by the model, using equations (18) and (19).

Figure 3 shows the meridional wind component at 700 mb. Figure 3A contains the values computed by the model when advection by the mean wind is neglected; and figure 3B contains the values when it is included. Figure 3C shows the observed normal 700-mb meridional wind distribution. Since the zero lines in these figures represent the position of ridges and troughs, comparison of 3A with 3B shows the eastward movement of these troughs and ridges obtained when advection by mean wind is included. The meridional wind distribution generated by the model (fig. 3B) is in remarkably good agreement with the observed values (fig. 3C).

Figure 4 shows the zonal component of the wind: 4A, the computed values when advection by mean wind is neglected; and 4B, the values when it is included. Figure 4C shows the observed normal zonal wind at 700 mb. Comparison of the computed with the observed values shows that the solution including advection (fig. 4B) is in better agreement with observations (fig. 4C) than the one without advection.

Next we shall explore the effect of advection of thermal energy by the mean wind and by ocean currents in predicting monthly anomalies of temperature. We shall consider the prediction at 700 mb for January 1968, summarized in figure 5. In figure 5A are shown the anomalies predicted when advection of thermal energy by the mean wind, by the mean ocean currents, and by migratory oceanic eddies have all been neglected. In 5B are the values predicted when only advection by mean wind is neglected, and in 5C are the values predicted when all three advections are included and option 6 has been used for the advection by the mean wind. Finally, in figure 5D are the observed 700-mb values. Comparison of figure 5B with 5A shows that the effect of including advection by ocean currents is not negligible. Its contribution intensifies the anomalies and introduces some pattern changes, especially over the oceans. The solution which includes advection by mean wind (fig. 5C) seems to be in better agreement with the observed values (fig. 5D) than the other two predictions.

In figure 6 are shown the anomalies of 700-mb tempertures for December 1967. Comparison of these anomalies with those predicted (fig. 5C) and observed (fig. 5D) for January 1968 shows that some of the important observed changes have been correctly predicted by the model.

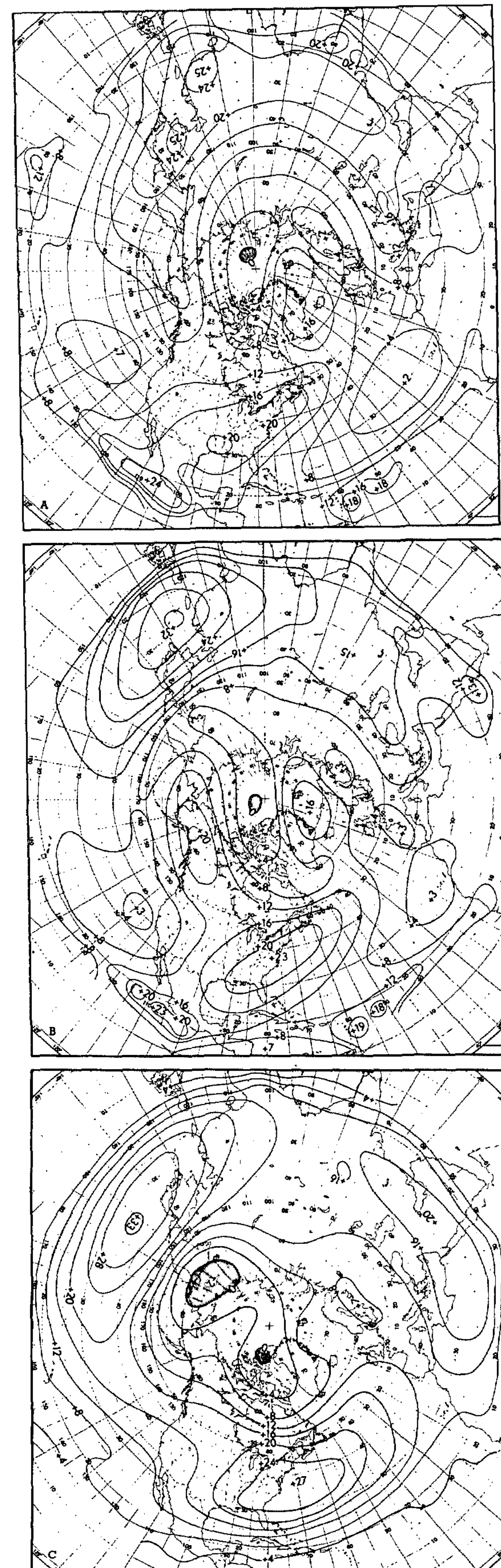

FIGURE 4.—Normal zonal wind components at 700 mb, in meters per second: (A) and (B) are computed, using equations (18) and (19), from the predicted temperature fields shown in figures 2A and 2B, respectively; and (C), observed geostrophic values.

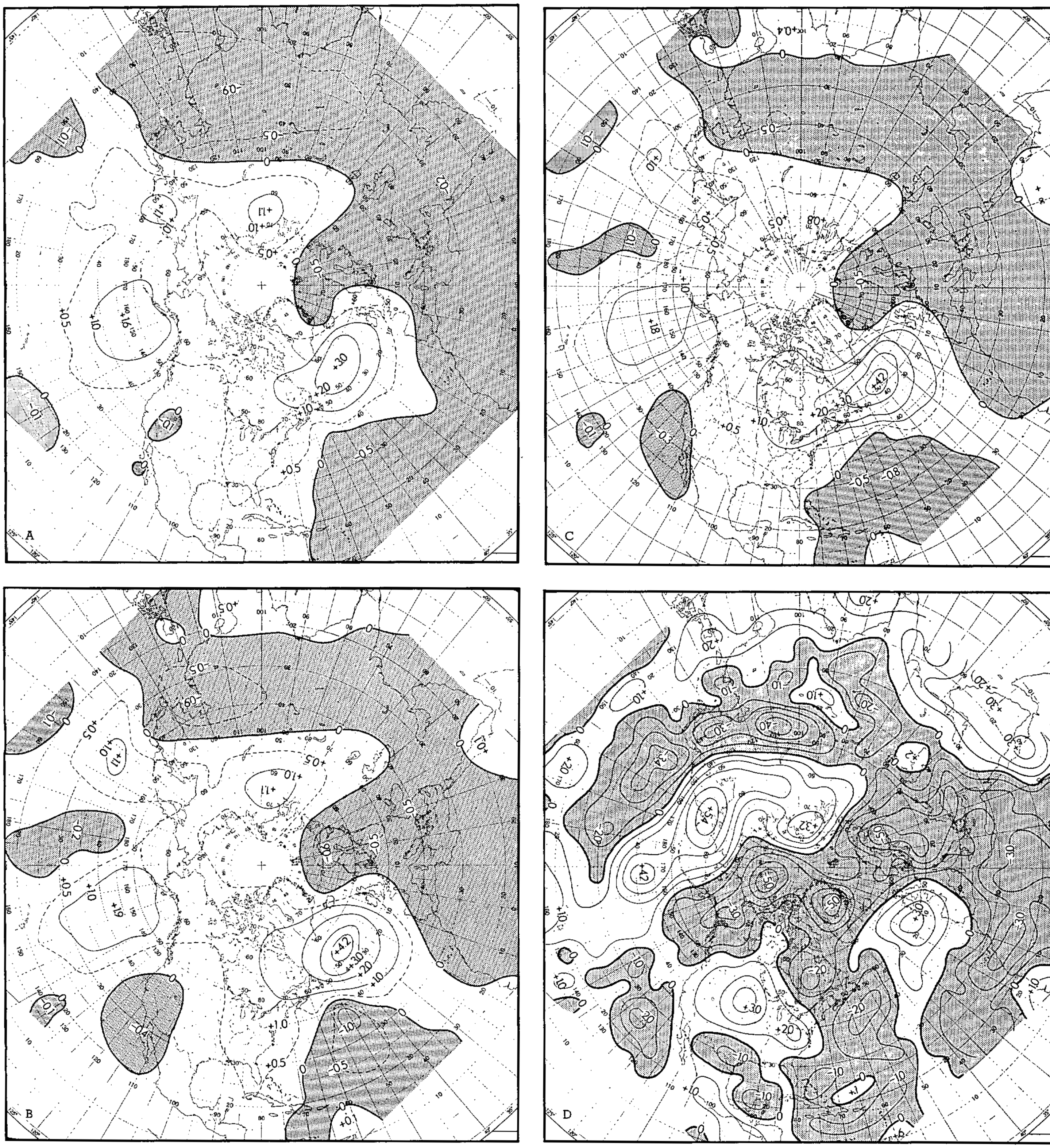

FIGURE 5.—The 700-mb temperature departures from normal for January 1968 in deg Celsius: (A) shows values predicted when the advection of heat by the mean wind, by the mean ocean currents, and by migratory ocean eddies have been neglected; (B) values predicted when only the advection by mean wind is neglected; (C), values predicted when the advection by all three terms are included; and (D), observed values.

Figure 7 shows the 700-mb horizontal wind anomalies: 7A and 7B are the predicted anomalies of the meridional and zonal components, respectively, corresponding to the prediction of temperature anomalies in figure 5C; and 7C and 7D, the corresponding observed values. Comparison of 7A with 7C, and 7B with 7D, shows that the patterns of the predicted anomalies, especially those of the meridional component, are in fair agreement with the observations, but the magnitudes of the anomalies are smaller than those observed.

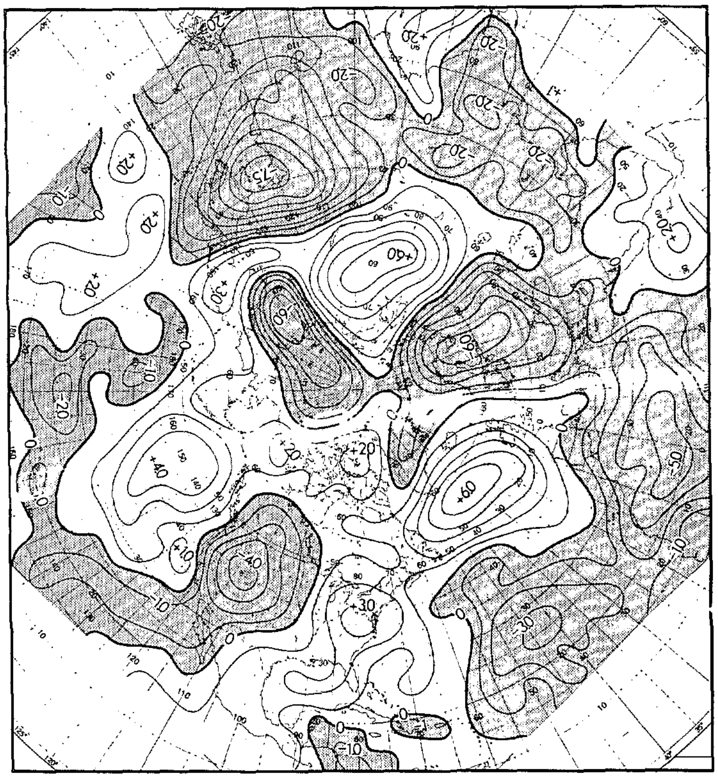

FIGURE 6.—The 700-mb observed temperature anomalies for December 1967.

Despite the lack of accuracy of the predicted wind anomalies, the ability of the model to generate them as well as the corresponding advective effect in the predicted temperature field is of the greatest importance.

For example in the case of figure 5 when advection is included (fig. 5C), the western part of the United States becomes warmer than when advection is neglected (fig. 5B). This is due to an above-normal southerly wind that was predicted by the model (fig. 7A) in agreement with observations (fig. 7C). This warming of the western part of the United States predicted by the model due to advection is in qualitative agreement with observations. In fact, observations show a strong reversal from negative anomaly for the previous month (fig. 6) to positive anomaly (fig. 5D).

In the prediction shown in figure 5C, we have used option 6 for the advection of heat by the mean wind. The prediction using option 5 yields the same results as option 6; and the other options yield, for this particular case, predictions with less skill than option 6.

5. EVALUATION OF THE PREDICTIONS FOR 1969

The importance of advection by the mean wind has been evident in the routine application of the model to 30-day prediction. In this section, its effect on the most recent cases is shown.

The whole year 1969 will be considered, but only those predictions for the calendar months are included.

The percentage of signs of monthly surface air temperature anomalies correctly predicted over the conterminous United States was verified. In these predictions, we have used only advection by the mean normal wind (option 2).

Table 1 shows a comparison of the percentage of sign correctly predicted by seasons and for the whole year, when advection by mean wind is neglected and when it is included. The results show a considerable improvement in the skill due to the mean wind advection, the average for the whole year being 14.3 percent. In table 2 is shown the skill of the model and of the official forecast, using persistence as control.

The first column of numbers shows the percentage of signs correctly predicted by persistence (using the previous month's anomalies as the prediction). The second and third columns show the percent of correct sign that the model predicted in excess of persistence: the values in the second column correspond to the predictions using advection by mean wind; those in the third column correspond to the predictions supplied on a real-time basis for possible use in the preparation of the official forecast. The differences between the values in the second and third columns are due to variations in the options of the model used. The biggest discrepancy corresponds to fall and is due to the fact that in October and November a model without advection was used in the predictions evaluated in the third column.

Finally, in the fourth column are shown the values of the excess over persistence of the official forecast. A comparison of the values in the second and third columns with those in the fourth column shows that, except for the fall season, the skill of the model was comparable to that of the official forecast.

TABLE 1.—*Percentage of correct sign of monthly surface air temperature anomalies predicted by the model during 1969 over the conterminuous United States*

Period	Model without advection	Model with advection	Difference
Winter	47.7	57.7	10.0
Sp ing	47.7	47.7	0
Summer	45.3	61.3	16.0
Fall	34.7	51.0	16.3
Average for 1969	43.8	54.4	10.6

TABLE 2.—*Percentage of correct sign of monthly surface air temperature anomalies predicted by the model and by the official forecast during 1969 over the conterminous United States*

Period	Persistence	Model with advection minus persistence	Real-time model minus persistence	Official forecast minus persistence
Winter	57.0	0.7	1.0	2.0
Spring	43.0	4.7	5.6	8.3
Summer	46.6	14.7	14.7	19.4
Fall	49.3	1.7	−7.0	11.8
Average for 1969	49.0	5.5	3.6	10.1

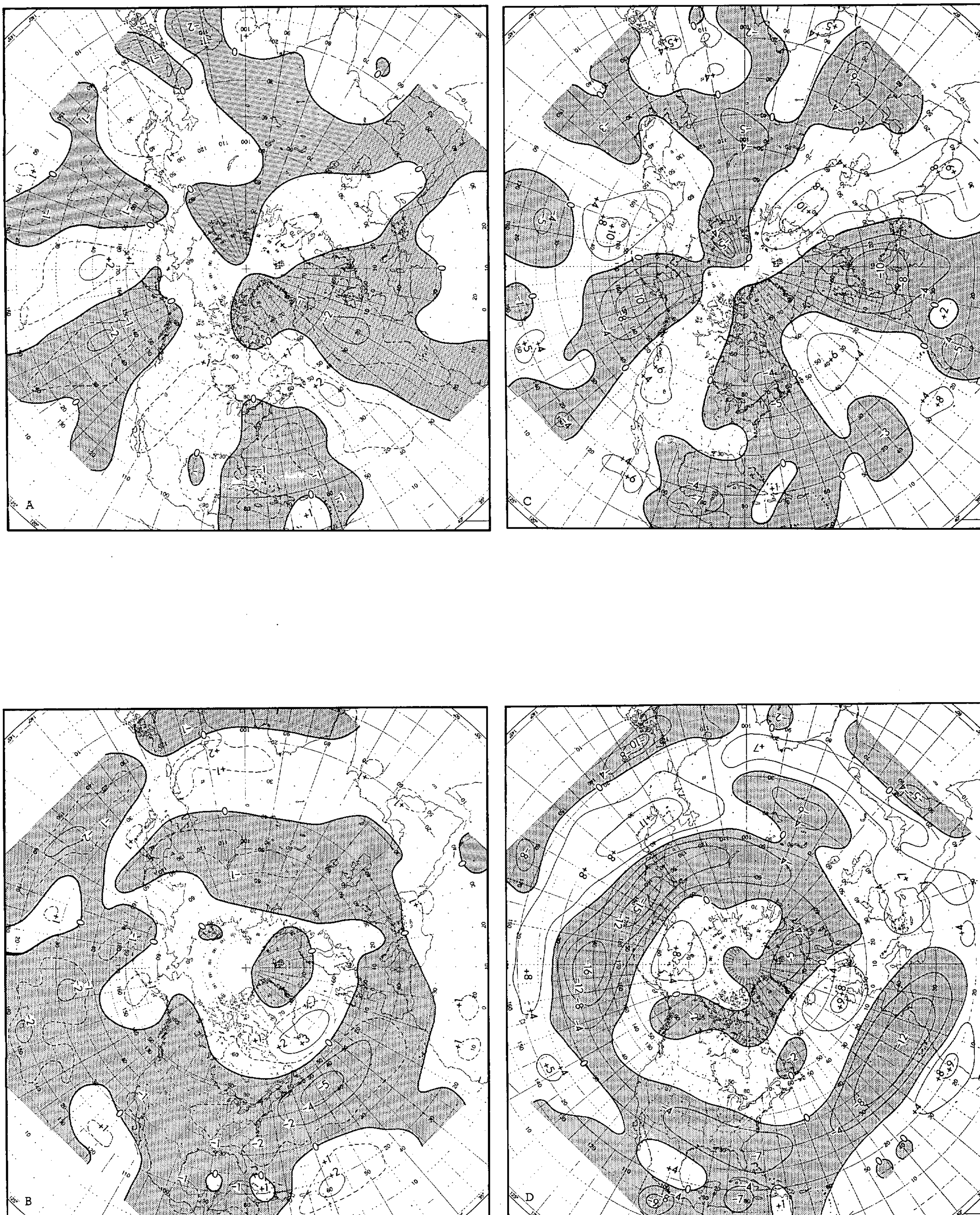

FIGURE 7.—The 700-mb horizontal wind departures from normal for January 1968, in meters per second: (A) and (B) are predicted meridional and zonal components, respectively; and (C) and (D) are observed geostrophic meridional and zonal components, respectively.

6. FINAL REMARKS AND CONCLUSIONS

We have attempted to incorporate the advection of thermal energy by mean wind and by ocean currents in the thermodynamic approach to long-range weather prediction.

The model presented seems to have the ability to predict mean wind anomalies that in turn introduce important nonnegligible changes in the predicted surface and 700-mb temperature anomalies.

The generated anomalies of advection of heat by ocean currents also introduce nonnegligible changes in the surface and 700-mb temperature anomalies, especially over the oceans.

For the cases considered in these numerical experiments, the predicted monthly anomalies of temperature seem to be in better agreement with observations when the advection terms are included.

An extensive series of experiments is now being conducted, including advection of thermal energy by the mean wind and by ocean currents. A variety of options is included to determine from the numerical experiments which combination of them yields the highest scores in the predictions.

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